2018
APPLIED ANTINEUTRINO PHYSICS WORKSHOP SUMMARY

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APPLICATIONS

- Nuclear nonproliferation monitoring from near and far
- Nuclear explosion monitoring
- Geoneutrinos

TOPICS

- Outcomes oriented engineering
- Near field detection projects
- Reactor flux predictions and reactor anomalies
- Far field detection projects
- Use cases and application studies
- Coherent neutrino-nucleus scattering
- Detection R&D

PHYSICS AND MONITORING WITH NEAR FIELD DETECTORS

- Physics goals:
  - Resolution of Reactor Antineutrino Anomaly: sterile neutrinos or predicted flux overestimation?
  - 5 MeV bump detection
  - Precision measurement of fissile fuel spectra: ^{235}U spectrum at research reactors, other spectra at commercial reactors through fuel evolution
  - CENNS

- Monitoring goals:
  - Surface operation
  - Portable
  - Spectra resolving capabilities for Pu monitoring – good energy resolution
  - Commercialized: low cost, preferably plastic, no special operation required after initial setup, results available by touching a button (increased Pu production detected or not?)

NEAR FIELD DETECTION PROJECTS

Vigorous activity in near field reactor antineutrino detection around the world!

11 listed experiments all deployed at reactor sites

PROSPECT (USA) by Pieter Mumm

STEREO (France) by Helena Almazan

SoLiD (Belgium) by Maja Verstraeten

CHANDLER (USA) by Jaewon Park

NEOS (Korea) by Bo-young Han

DANSS (Russia) by Yuri Shitov

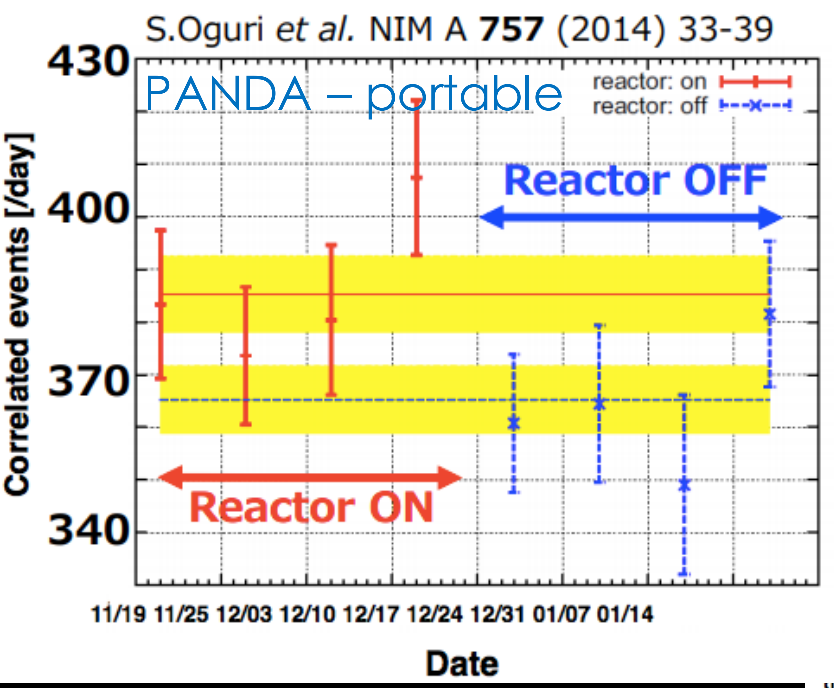
Neutrino4 (Russia) by Anatolii Serebrov

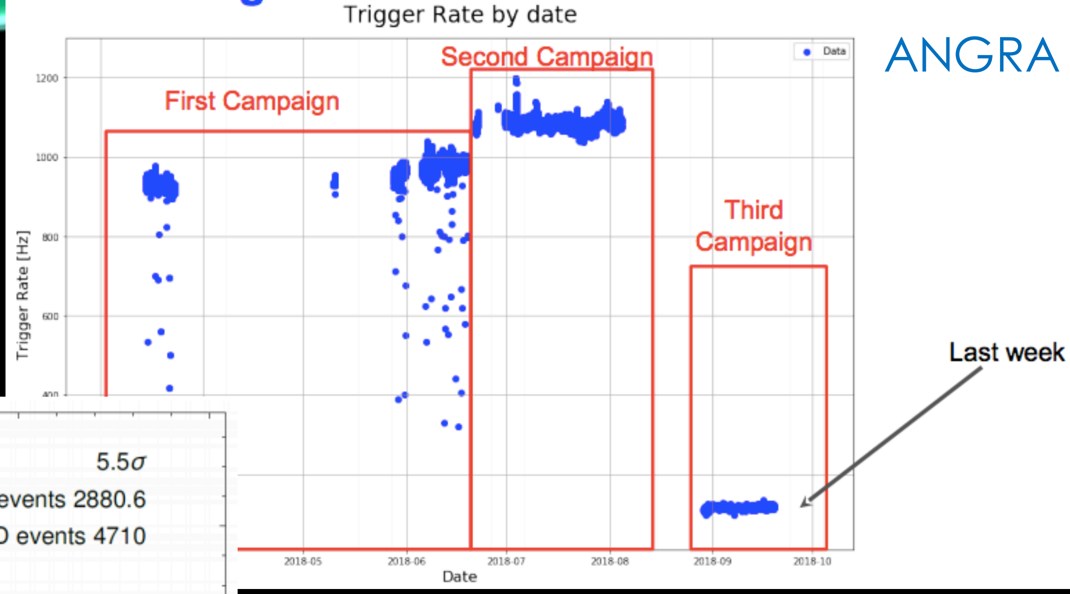
Status of reactor neutrino monitor experiments in Japan by Kyohei Nakajima

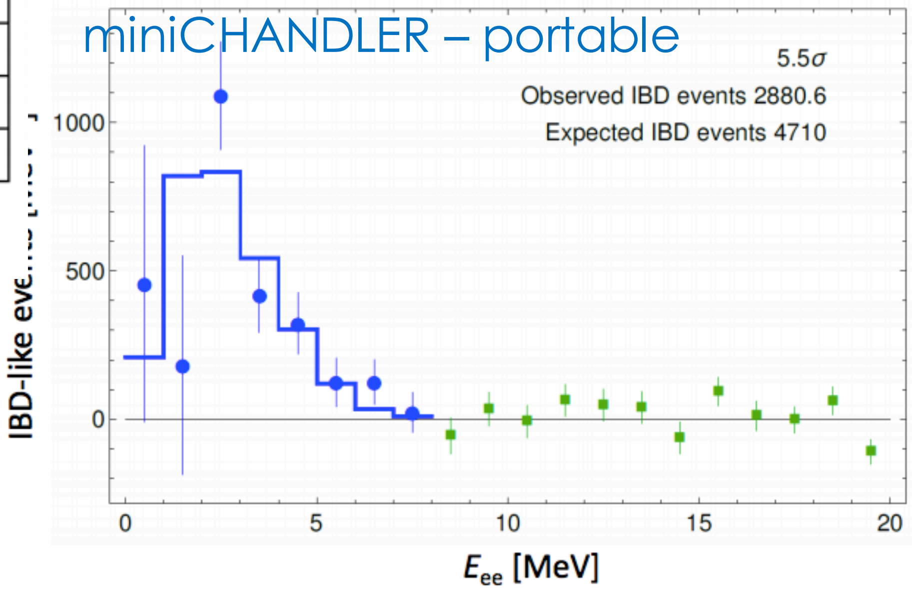
Status of the Neutrinos Angra Project (Brazil) by Pietro Chimenti

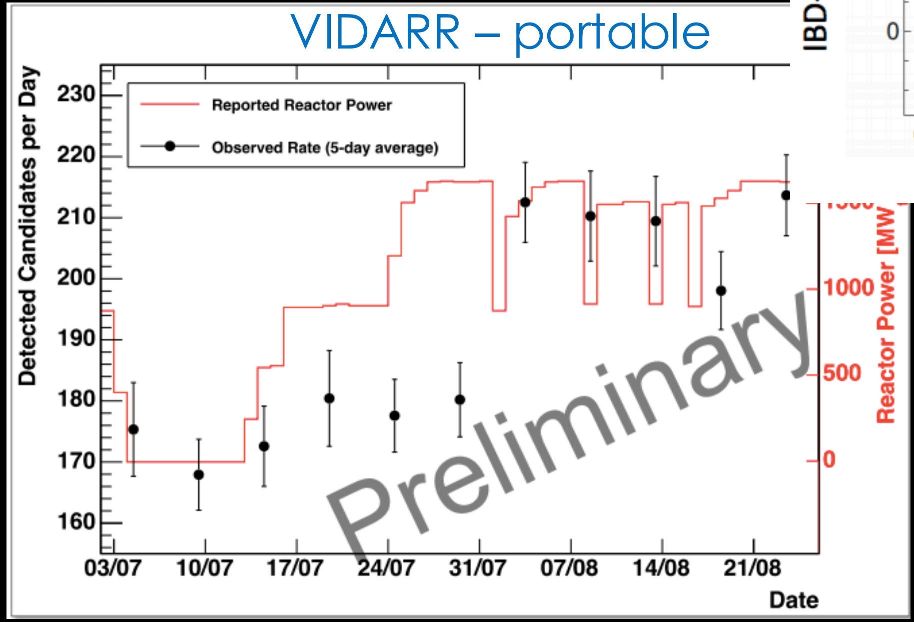
Vidarr (UK) by Jonathan Coleman

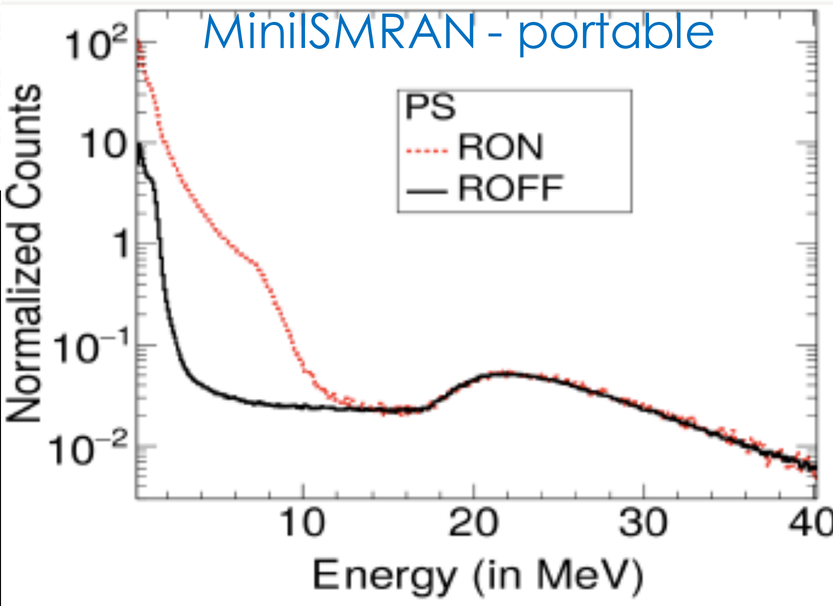
ISMRAN (India) by Dhruv Mulmule (presented by N. Bowden)











DEPLOYMENTS AT REACTOR SITES

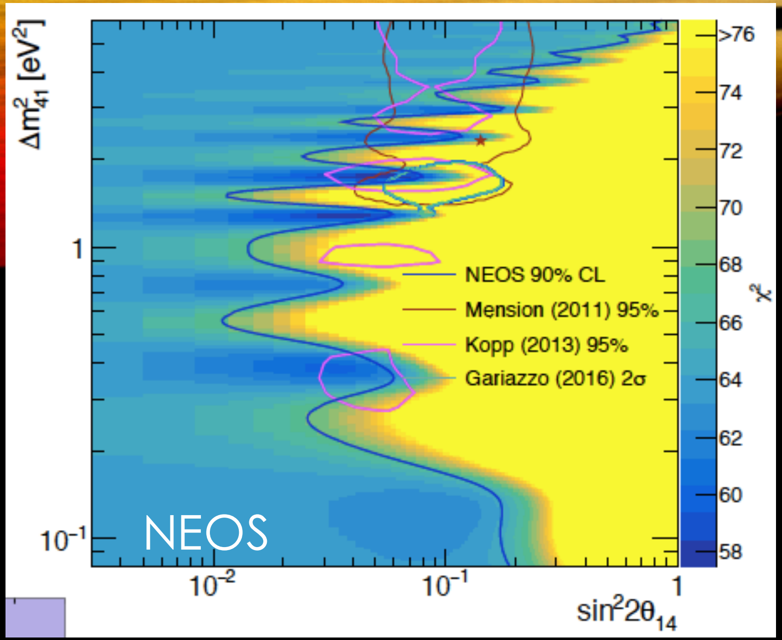
NEAR FIELD DETECTORS TAKING PHYSICS DATA

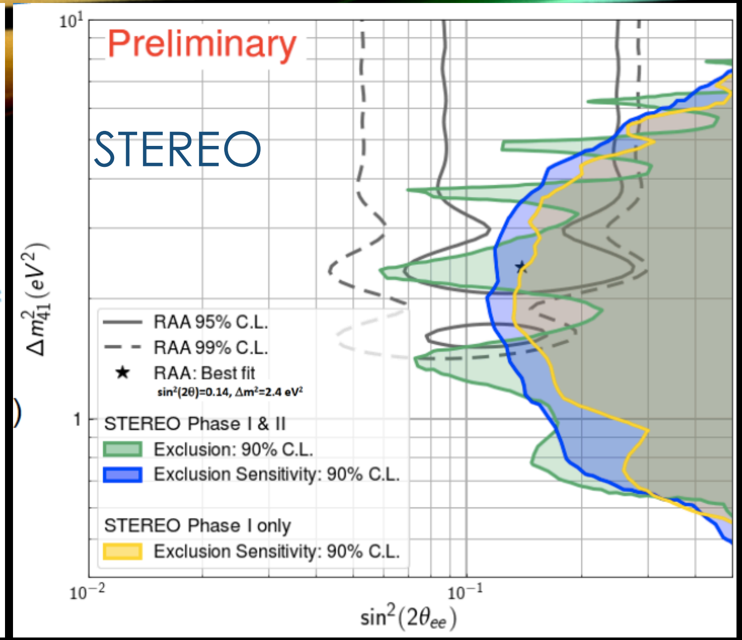
PROSPECT, STEREO, SoLiD , NEOS, DANSS, Neutrino-4 – taking reactor antineutrino data
In their final configuration

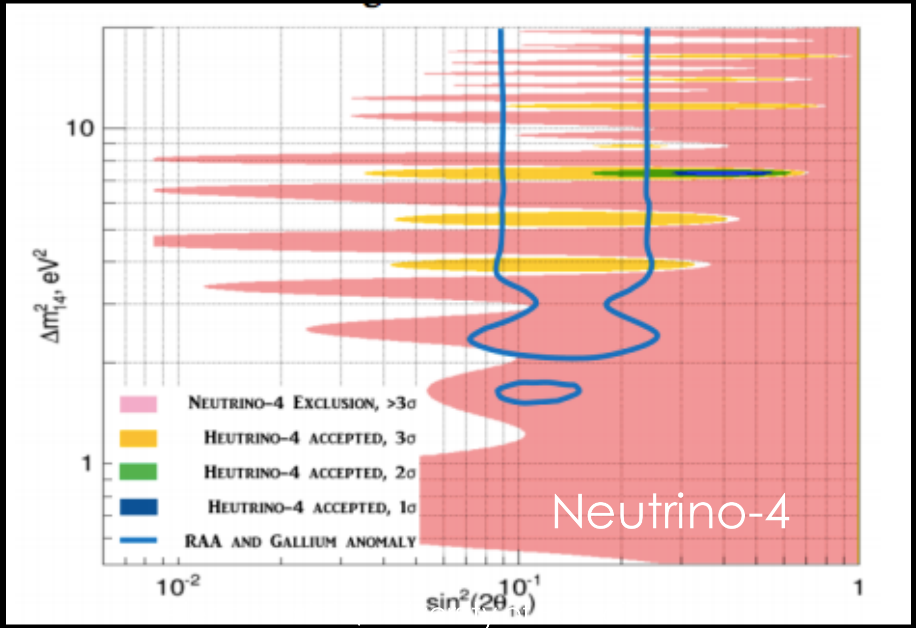
Reactor antineutrino detection on the surface with no/or minimal overburden:
PROSPECT, SoLiD (challenging signal to noise), MiniCHANDLER!

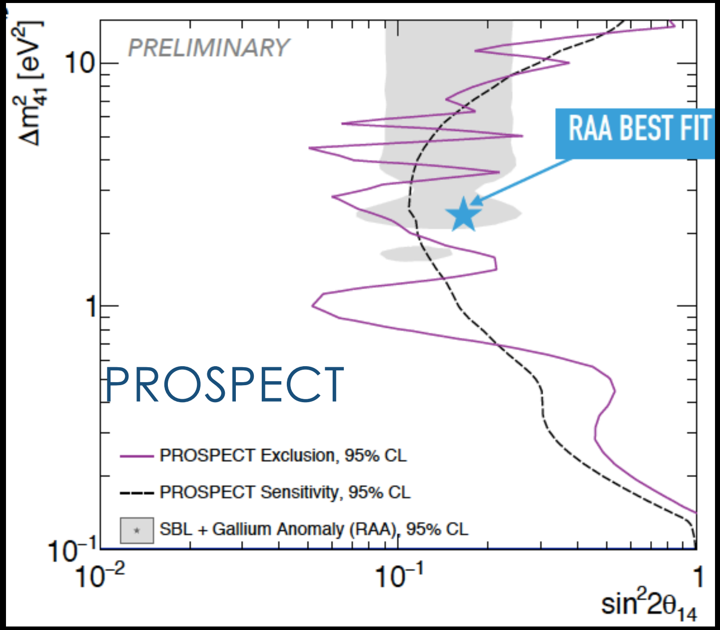
Successful antineutrino detection:
- at research and commercial reactors alike,
- with plastic and liquid scintillators,
- Gd and Li doping, monolithic and segmented geometries
- demonstrated power of PSD!

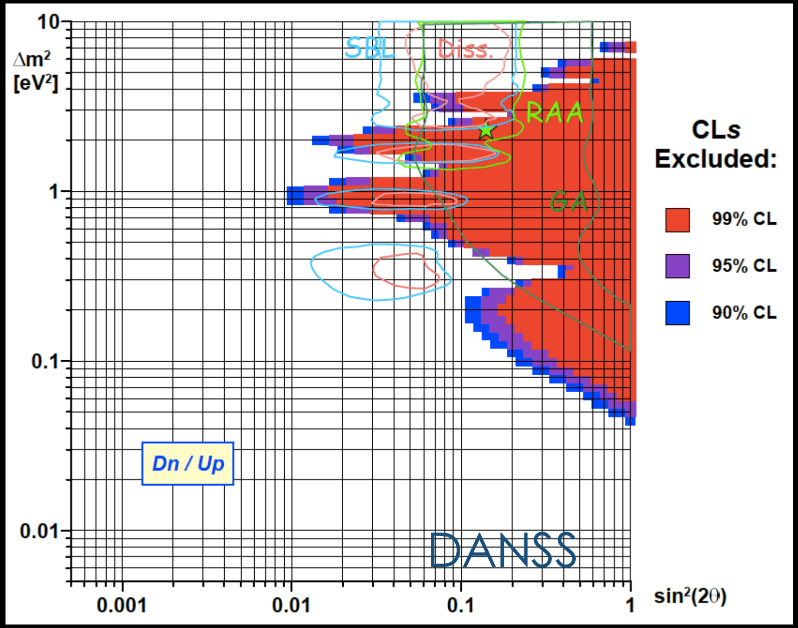
DATA DISFAVORS RAA BEST FIT BETWEEN 2-5 σ



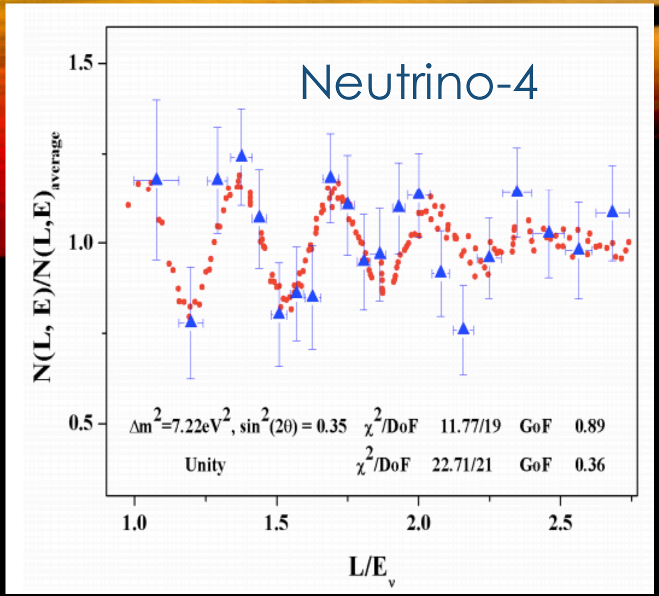




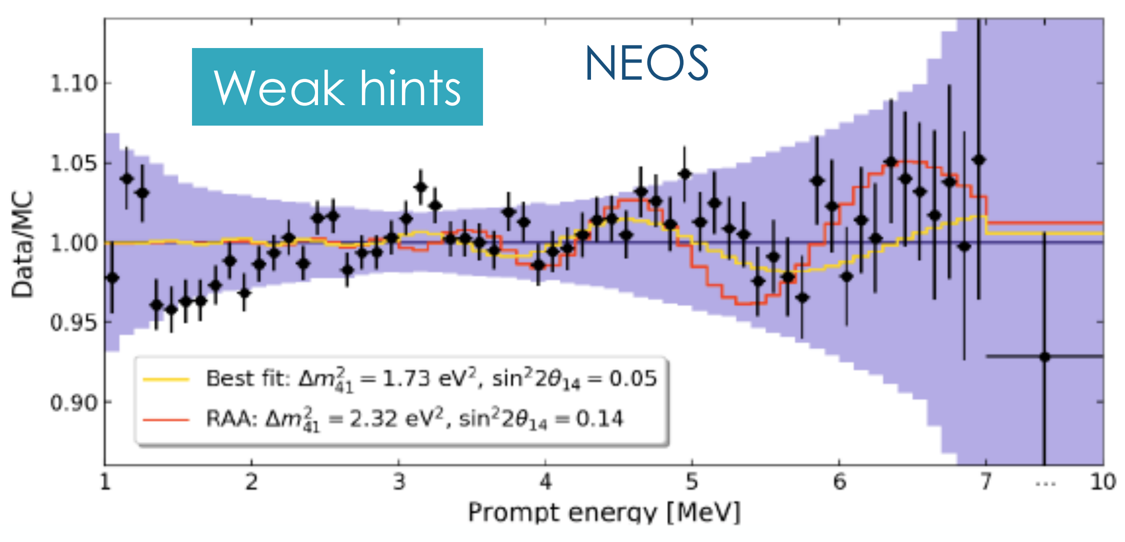


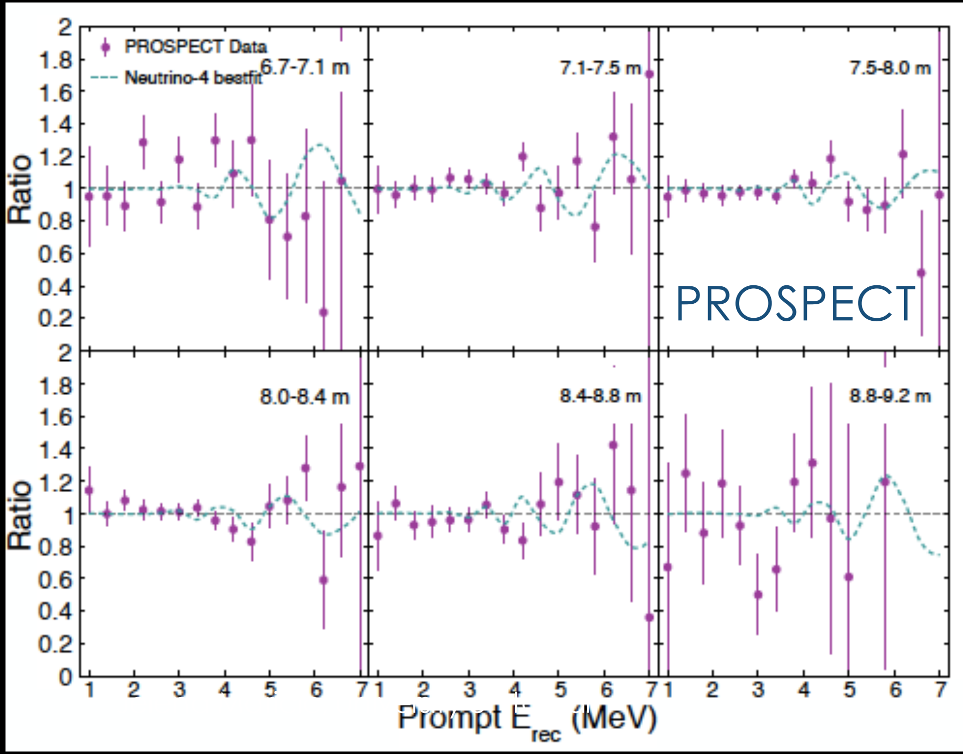


CONFLICTING STERILE NEUTRINO HINTS

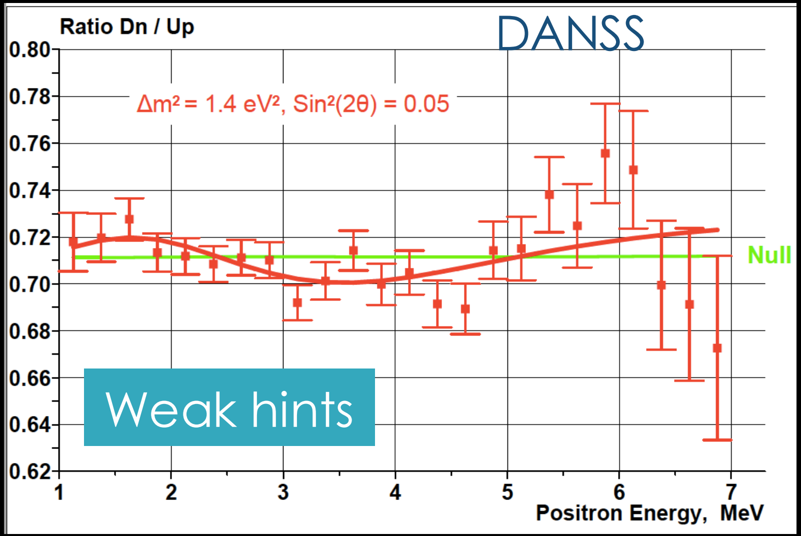


Strong hints, **but** issues with spectrum and correlations treatment. Implies large mixing angle: inconsistent with DB RENO, DC





PROSPECT data - poor Fit for Nu4 Best fit point.

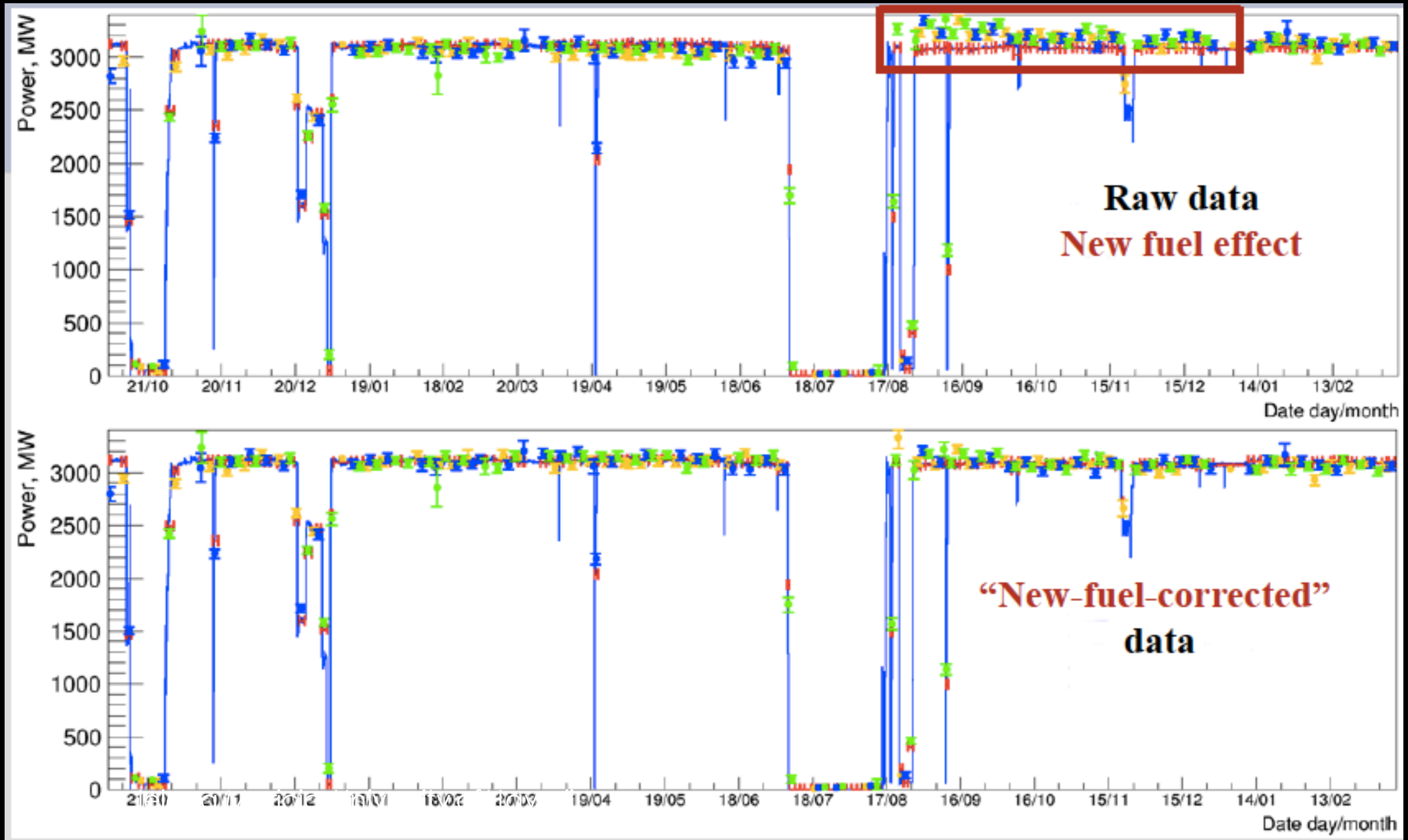


^{235}U SPECTRA AND U-Pu CONTENT IN FUEL

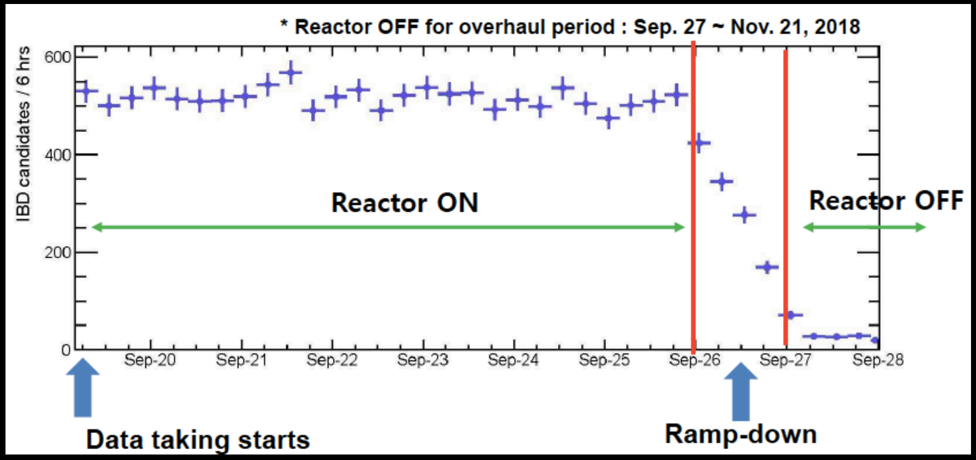
PROSPECT and STEREO next step:
precision ^{235}U spectrum measurement.

Neutrino4 measured spectrum –excess issues.

DANSS sensitive to U-Pu content in fuel.



NEOS II – spectrum evolution with fuel composition – run just started.



NEXT STEPS IN NEAR FIELD DETECTORS

- With neutrino flavor picture getting more convoluted, additional experimental measurements required
- Several incoming players: CHANDLER, ANGRA, ISMRAN, VIDARR, Japanese near field detectors (PANDA, LS monitor)

Reactor monitoring with antineutrinos for safeguard applications is a reality!

Much closer to the dream: off-the-shelf antineutrino reactor monitor.

REACTOR FLUX PREDICTIONS AND REACTOR ANOMALIES

Flux predictions from theory by Anna Hayes

Flux predictions from experiments by Alejandro Sonzogni

Updated Flux and Spectral Predictions relevant to the RAA by Anthony Onillion

Overview and Status of Anomalies by Georgia Karagiorgi

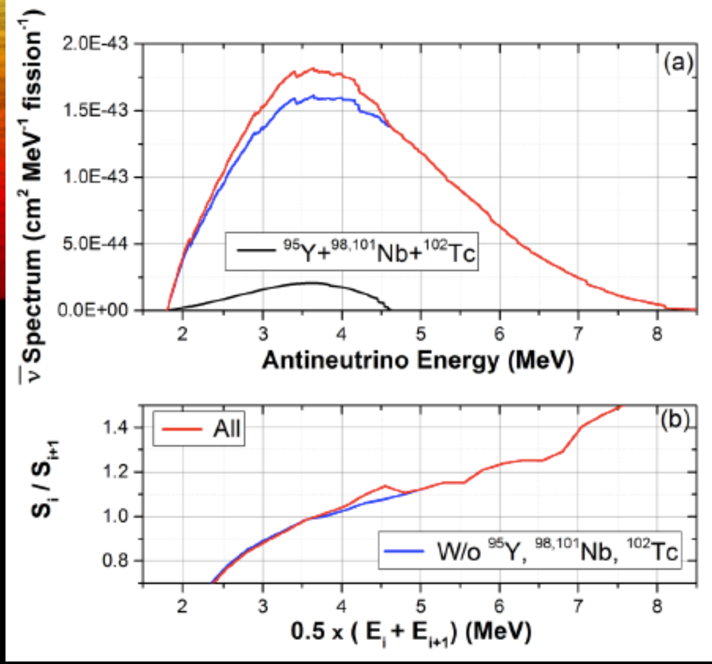
RECONCILING ANOMALIES – FLUX PREDICTIONS

- Simultaneous fit of the DB antinu spectrum and the equivalent aggregate beta-spectrum with (1) point-wise Zeff and (2)improved descriptions of forbidden transitions **reduces the RAA from 5% to 2.5%**
- The magnitude of the IBD cross sections change, depending on assumptions,
- but not the ratio of one isotope to another

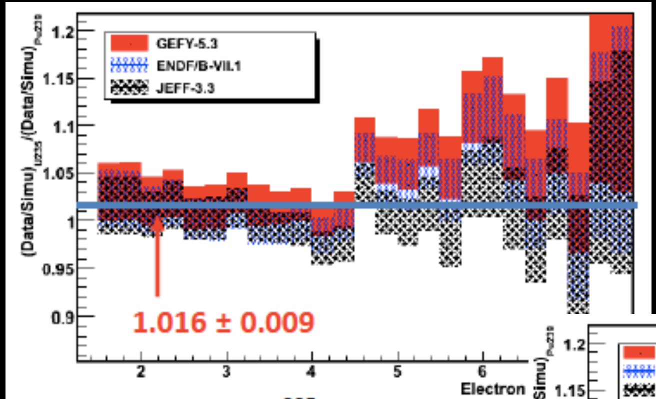
	all allowed $Z_{\rm eff}^{\rm Huber}$	all allowed $Z_{\rm eff}$	allow.+forbid. $Z_{\rm eff}$	allow.+forbid. $(Z_{\rm eff}^2)^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
^{239}Pu	4.36	4.3	4.22	4.23
ratio	1.534	1.530	1.533	1.532

- Spectral uncertainties have no consequences for JUNO.
- 5 MeV bump due to standard nuclear physics issues: hard spectrum of ^{238}U or ^{235}U according to Neutrino4
- DB measurement of ^{235}U/^{239}Pu differs from Schreckenbach prediction → NEOS

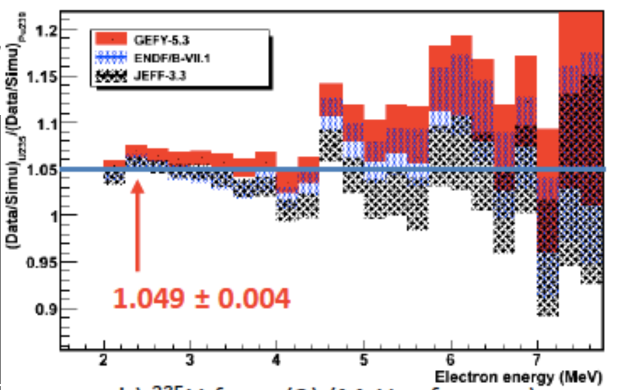
RECONCILING ANOMALIES – FLUX PREDICTIONS FROM DATA



Hard to defend on its own.



a) ^{235}U from (1)

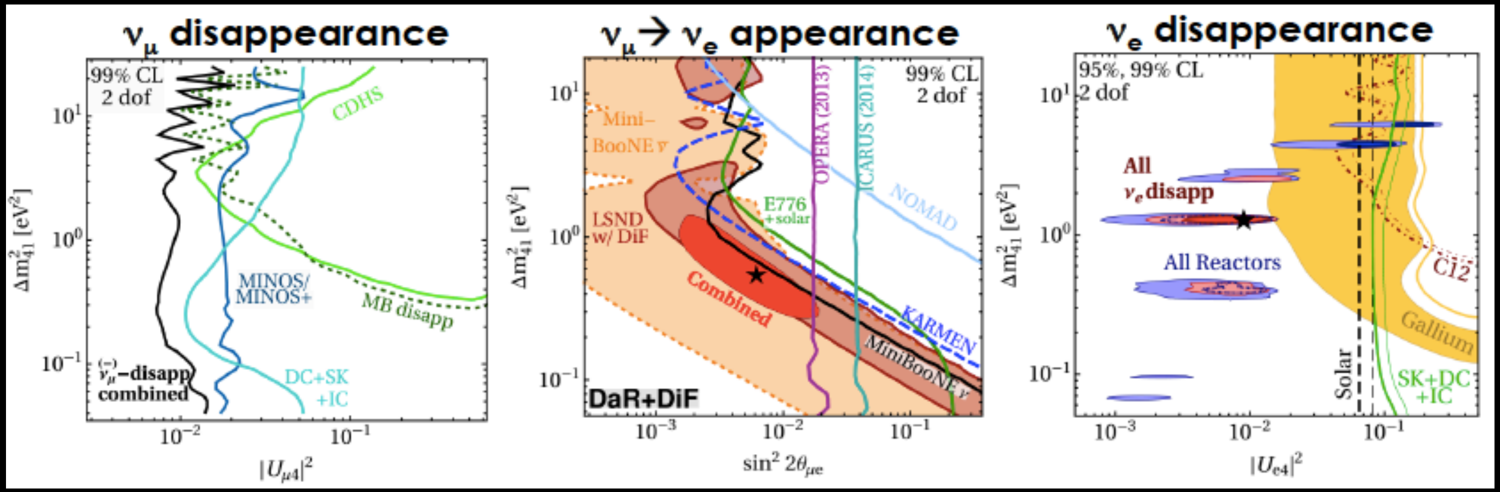


b) ^{235}U from (2) (M-H reference)

- Summation method from the nuclear data base reproduces fine structures in NEOS and DB spectrum and identifies responsible isotopes → nuclear detective at work!
- Preservation of neutrino experimental data crucial → *IBD spectrum as function of antineutrino energy in absolute units, together with its covariance matrix.*
- Normalization of ILL spectra underway: 5% inconsistency between two ^{235}U and ^{239}Pu measurements, but effect on RAA still being evaluated.

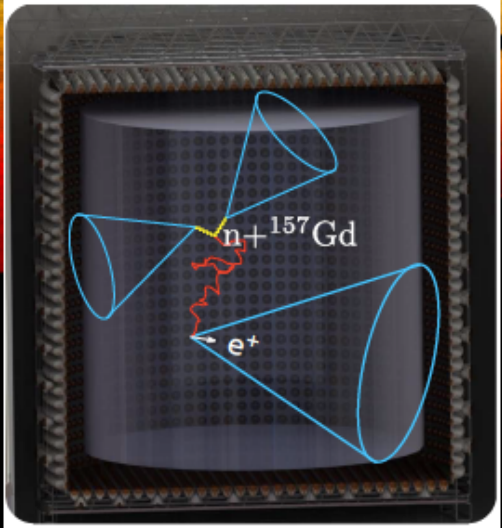
RECONCILING ANOMALIES – GLOBAL FITS

- *Global neutrino fits exhibit strong tension – 3+1, up to 3+N do not fix the problem with no signal in ν_μ disappearance channel. Need to add decay, or…*

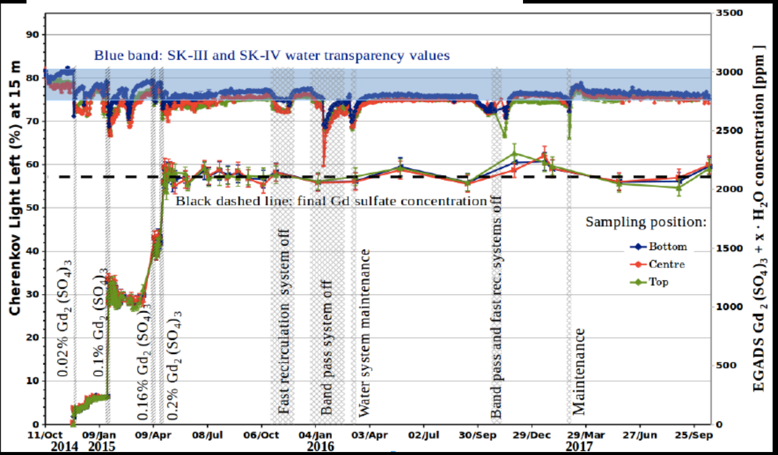


- *Weighted statistical treatment of inputs essential.*
- *Without rethinking the statistical approach, difficult to see how additional experimental results can reconcile existing tensions completely.*

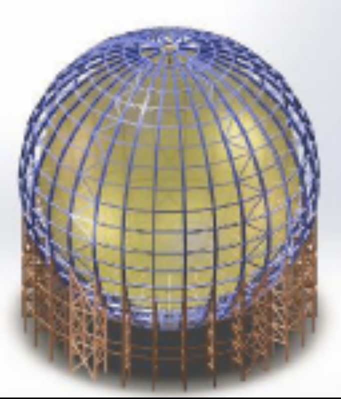
FAR FIELD DETECTION PROJECTS



AMAZING PROGRESS IN LARGE SCALE DETECTORS



- WATCHMAN (1 kton) fully funded – medium range reactor detection. Schedule to start in 2023.
- Testbed for technologies: LAPPDs, WbS, balloon KL style.
- 300 days to confirm on-off cycle at Boulby at 25 km standoff at 3 sigma C.L.
- SuperK gadolinium (50 kton) on the way, taking data soon – far field → relic supernovae, but also detection of reactor antineutrinos may be possible even from Korea. EGADS convincingly demonstrated Gd loading in water at large volumes.
- JUNO (20 kton) – the largest LS detector - start in 2021. Reactor neutrinos at 53 km standoff. State-of-the-art in terms of energy resolution and energy scale linearity. 1.1 geoneutrinos/day (but with high level of backgrounds)



USE CASES AND APPLICATION STUDIES

Safeguards Policy Overview by George Anzelon

Antineutrino Detection Use Case Overview by Patrick Huber

Versatile Test Reactor (VTR) Overview by Tony Hill

Nuclear Explosion Monitoring: An overview of the global monitoring system by Michael Foxe

Explosion monitoring: What can neutrinos add to the global system?, by Rachel Carr

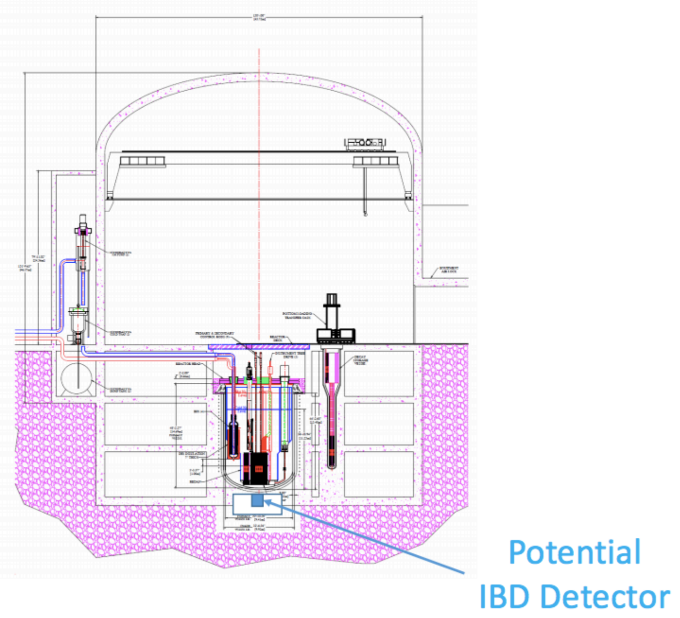
SAFEGUARD POLICY OVERVIEW AND USE CASES

- Within IAEA huge effort goes in reactor monitoring – 1/3 of IAEA personnel
- Nevertheless, IAEA happy with its system: need more attractive solutions like cost reduction, ease of use, finding alternative funding resource
- Antinus most helpful in specific cases: certain reactor types, hard to access reactors, far field detection, burnup of extra plutonium…

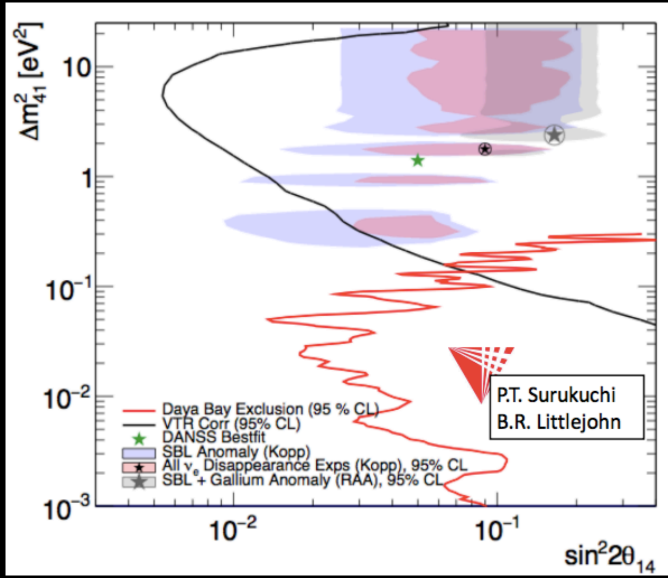
- Model reactor cases – detecting 10s of MWth reactors for Pu production from 20 m with PROSPECT like detector: detector on-off within hours to a day
- 2 km for far field monitoring of kton scale Daya Bay
- One can detect change in the fuel after a glitch (interruption in monitoring) within a week
- Reactor swap detection – more difficult, but doable within few months. Challenges with graphite moderator and Natural Uranium fuel reactors – low neutrn flux
- Strontium signature for spent fuel – low rates and below 3 MeV, so very challenging: require bkg reduction, and god far large quantities.

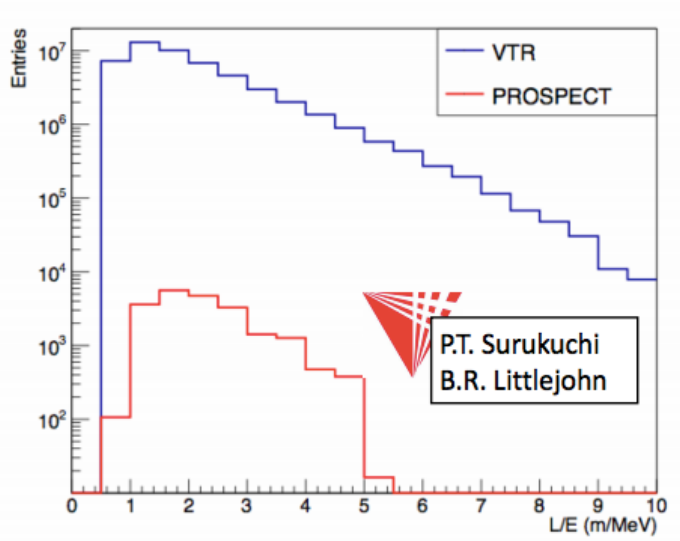
VERSATILE TEST REACTOR

- VTR – to test advance reactor technologies
- Accommodate several tests at once
- Supports new generation of high-value nuclear experiments
- VTR R&D funding awarded to GIT, Yale and IIT for IBD study
- Fast 300 MW reactor with stable isotopic fuel composition over the cycle



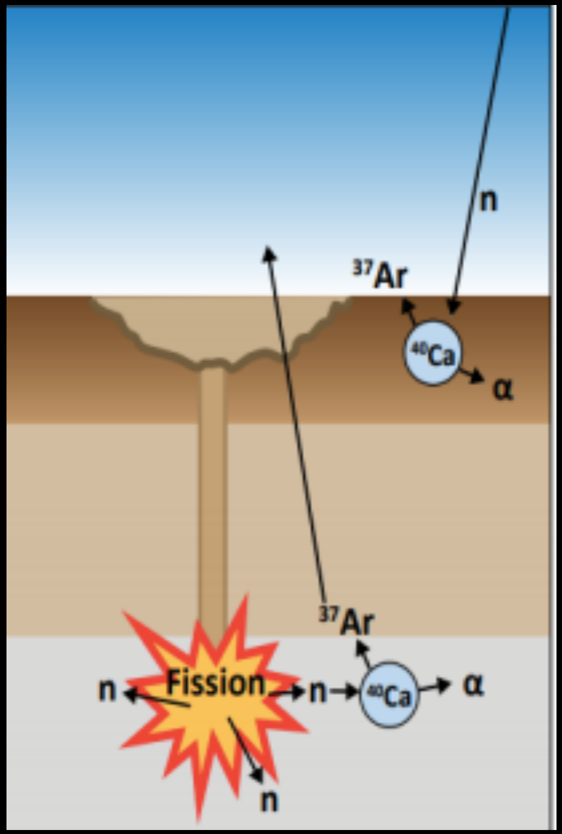
- **VTR has an opportunity for a dedicated neutrino gallery: nu spectrum shape, beta spectroscopy, fission product yields**
- **Critical decisions made by 2021**





NUCLEAR BOMB MONITORING

- Monitoring seismic signature with sensors and escaped gases generated in explosion
- Large sensor network exists - Just 11 sensors in the oceans required
- 0.5 kton explosion detection →109 km^2 area localization
- Just 11 sensors in the oceans required to monitor around world
- Infrasound – 60 stations around the world
- 80 particulate stations + Radionuclide noble gas detection
- To add capabilities with neutrinos: 1 kton detection, at 1000 km stand-off
- Even seismic trigger, 10x HyperK to detect 250 kton at 900 km → *does not justify the cost*



COHERENT NEUTRINO-NUCLEUS SCATTERING

CONNIE by Juan Estrada

COHERENT by Belkis Cabrera-Palmer

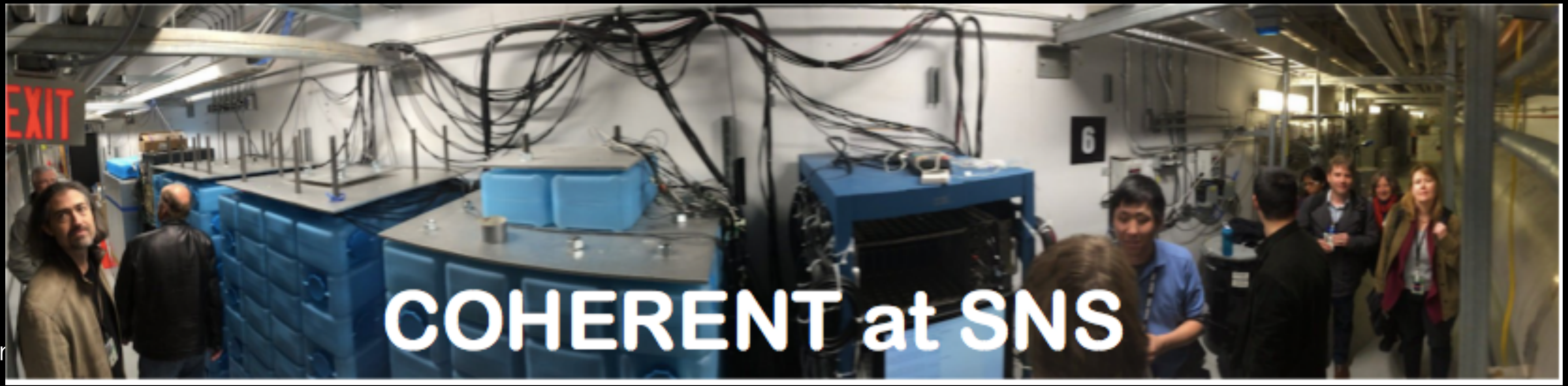
CONUS by Janina Hakenmüller

Prospects for reactor monitoring using noble liquid detectors by Jingke Xu

Ricochet by Joseph Johnston

COHERENT AT SNS

- Confirmed alternative reactor neutrino detection channel – difficult to measure keV depositions from nuclear recoil signals
- Accumulate more statistics with CsI[Na]
- CEnNS detection with multiple targets: expecting LAr, NINs detection for Lead and Iron – important for understanding nuclear effects
- New deployments:
  - low-threshold Ge detectors
  - Measure SNS n flux •
  - High precision CEvNS studies, physics beyond SM, n CC to support Supernovae physics and Weak interaction physics (Lead, Argon, Oxygen, Iodine)

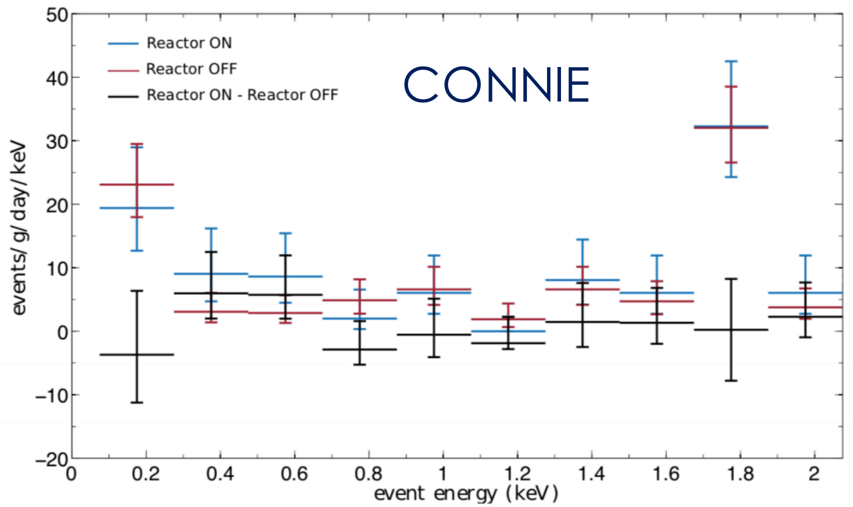


CONNIE, CONUS AND RICOCHET

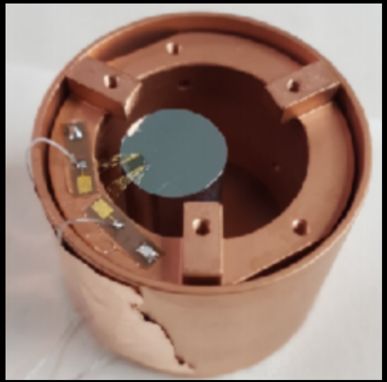
- CENNS with commercial nuclear reactor neutrinos yet to be seen.
- CONUS very close - Observation of an excess in the ROI at a statistical significance of 2.4 sigma at Brokdorf
- CONNIE – utilizes CCD technology – no noise (skipper CCDS),very promising.

  Going to second phase at ANGRA.
- RICOCHET – bolometers – deployment of first phase very soon at Chooz.

CONUS



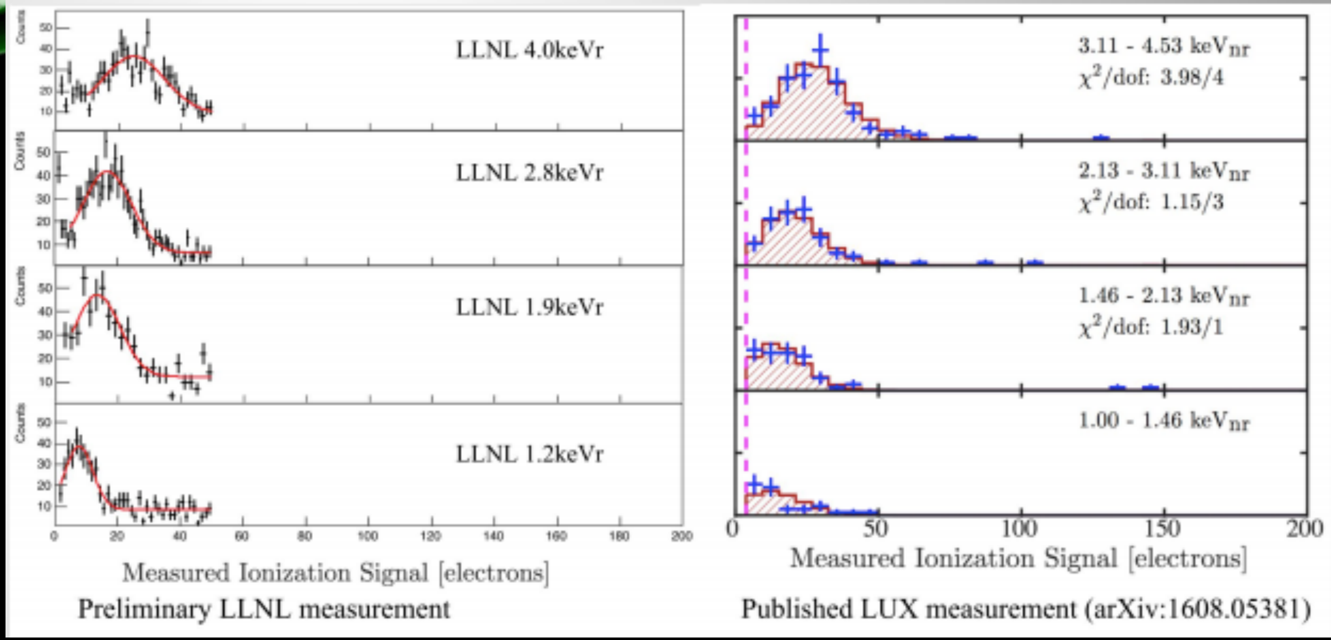
RICOCHET

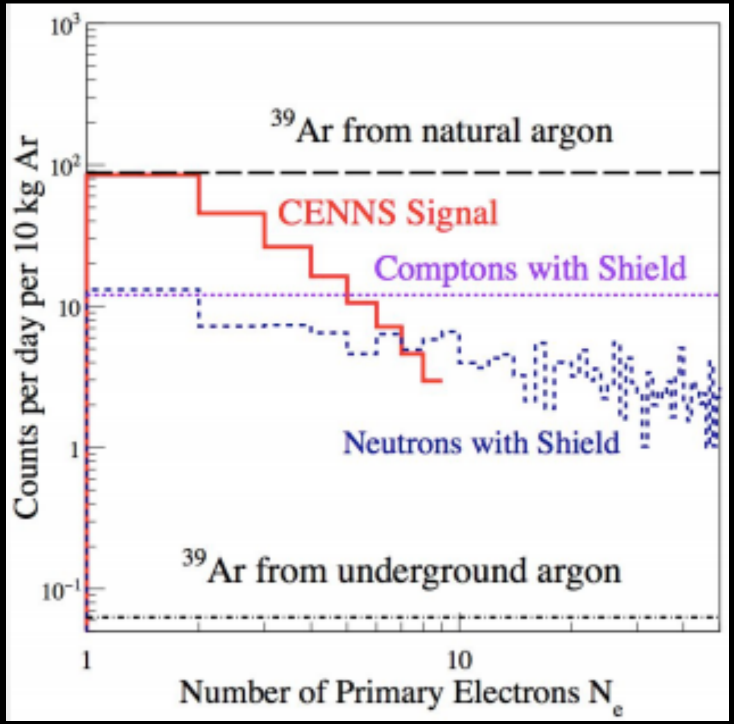


NOBLE LIQUID GASES

- Dual phase noble gas TPCs
- Developed for DM detection
- Sensitive to small depositions from nuclear recoil
- Xe – self-shielding, low intrinsic bkg, but suffers from instrumental bkgs
- Ar – removal of ^{39}Ar solved, 10^8 PSD
- Suitable for CENNS, but not demonstrated.
- Need calibration at low energy
- Never before used in near surface mode!

- Ongoing R&D at LLNL, IHEP, RED100 deployment at Kalinnin reactor!





DETECTION R&D

NuLat by John Learned

LLNL Materials Development by Andrew Mabe

BNL Materials Development by Minfang Yeh

Large-scale WbLS Detector R&D by Gabriel Orebi Gann

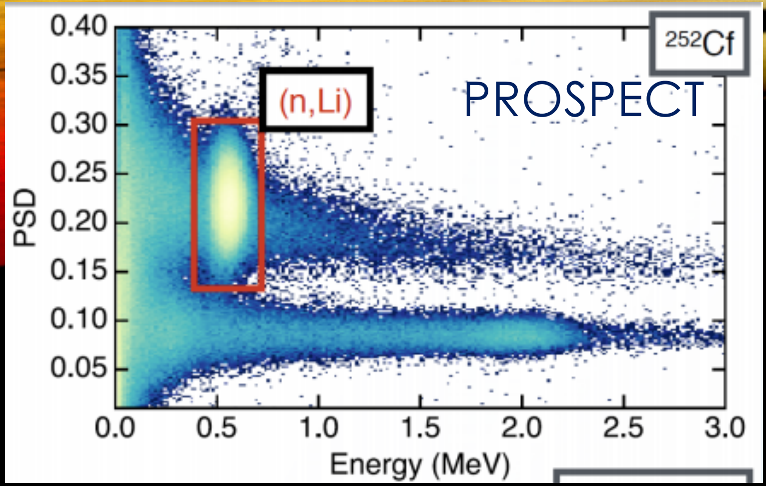
On-Surface Background Studies by Michael Mendenhall

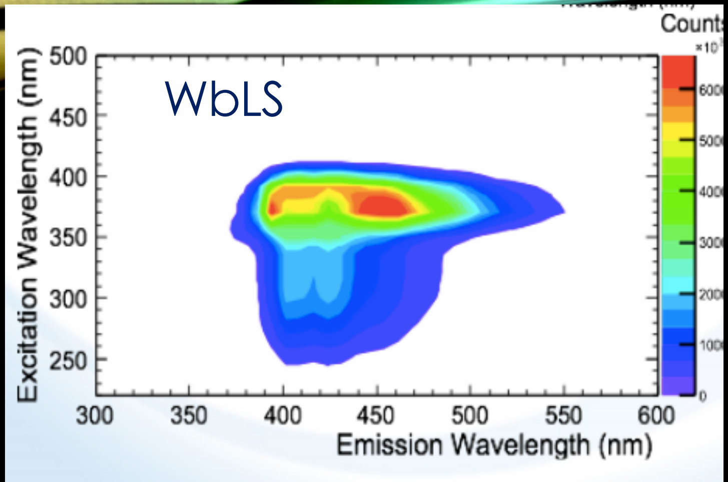
Antineutrino Directionality R&D by Daine Danielson

Distributed Imaging for Liquid Scintillation Detectors by Giorgio Gratta

SVSC: Development Towards a Compact Neutron Imager by Josh Brown

VERSATILE R&D ACTIVITIES





- NuLat – full 3D segmentation, with superb event topology, Li-loaded liquid scintillator, utilizes TIR for powerful background rejection.
- LLNL PSD plastic scintillators – goal: as good as LS; chemistry magic to stabilize PPO, increase loading, clarity of plastic. In 2018 success, EJ-276. 0.4%Li loading.
- BNL material deployment: WbLS, oil –like and water-like,

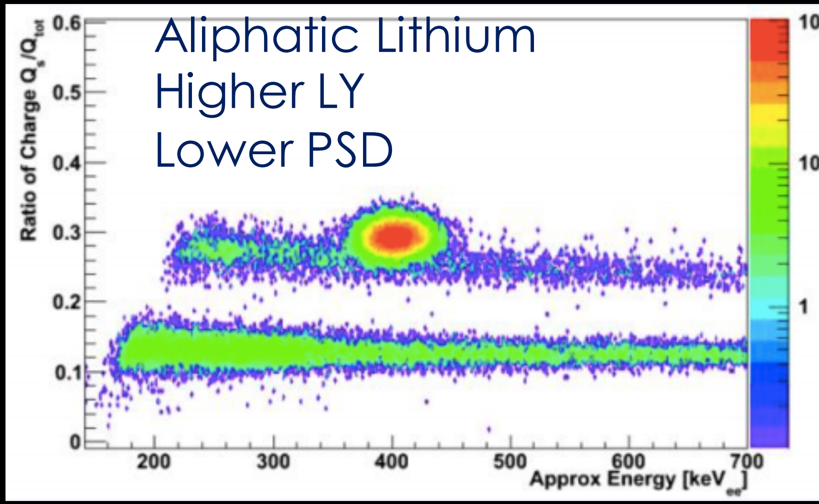
  allow doping – cost-effective for large detectors.

  Safer and more environmentally friendly than in the past.

  Water-based mixing efficient for 6Li loading – PROSPECT.

  Separation of Cherenkov from scintillation for directionality.

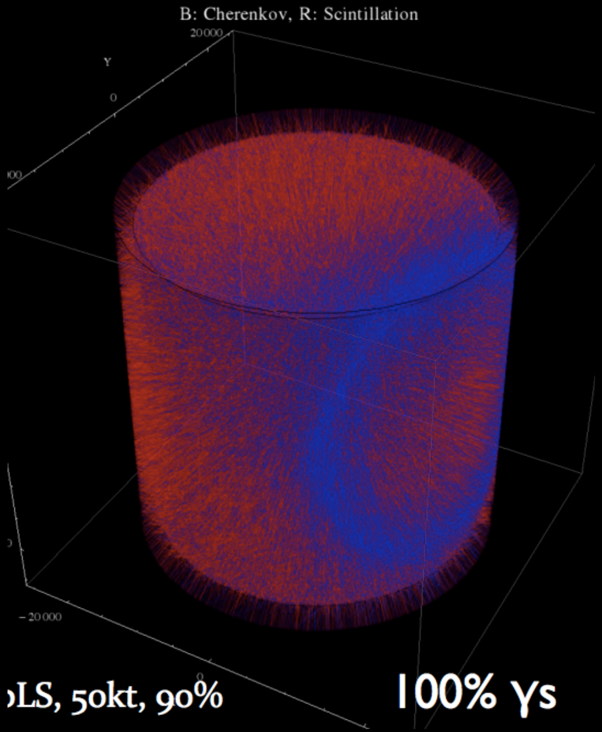
  Large quantity mixing in situ.



R&D FOR LARGE DETECTORS

- Large scale WbLS detector R&D – THEIA (50-100 kton) with powerful physics program. Cherenkov-scintillation separation in charge and time, PMT development, nanofiltration, time profile→WbLS much shorter time constant.

- Directionality with antineutrinos: Gd loaded LS in WATCHMAN – use direction defined by positron and neutron vertices.
  Works! 3σ detection of the unknown reactor is likely within 5 weeks @ 3 km, 15-16 weeks @ 4 km, and 52-60 weeks @ 5 km



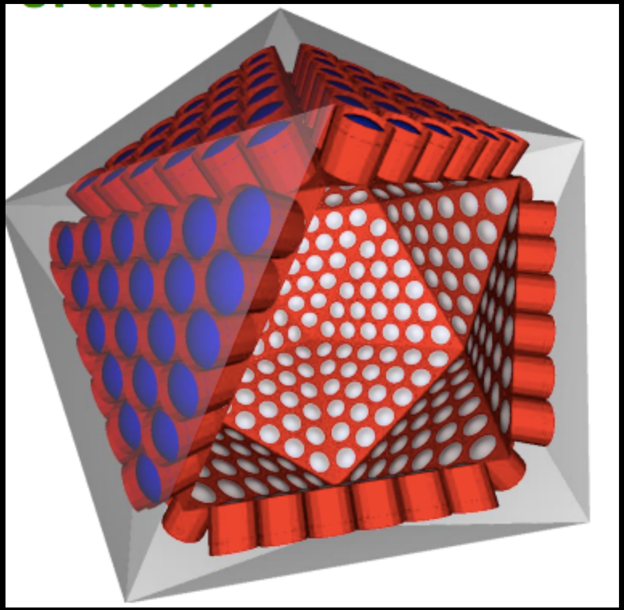
PREDICTING NEAR SURFACE BACKGROUND FOR TON-SCALE DETECTORS

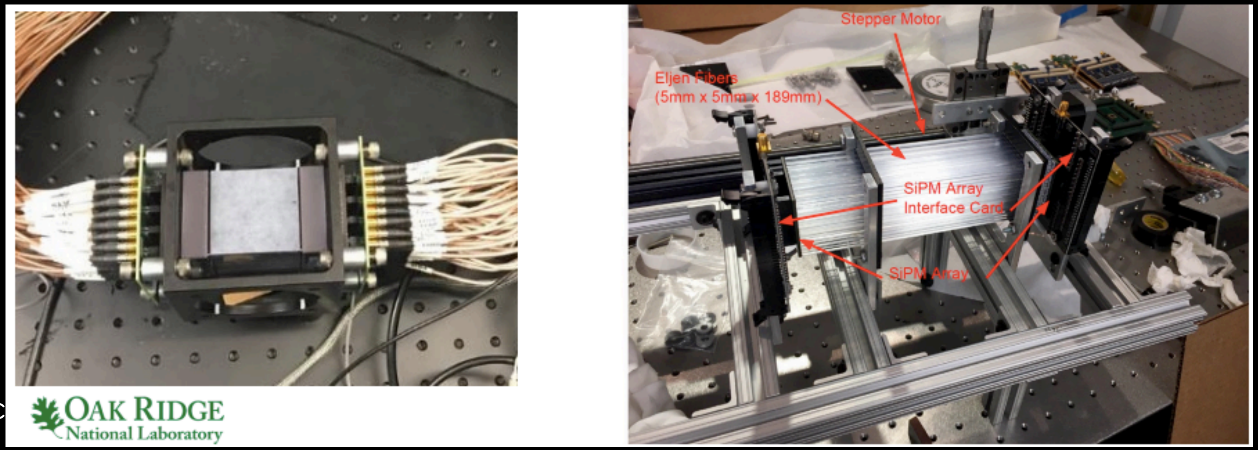
- Detailed simulation cross-checked by PROSPECT
- Importance for designing portable detectors and deployment at various locations.
- Cosmic fast neutrons produce most near-surface correlated backgrounds. I
- Versatile detector capabilities are critical.
- Segmentation and PSD essential for prompt IBD event identification.

R&D FOR IMAGING

- Imaging in scintillation detectors can do much better: use lenses to pixelate large area photodetectors. Timing and better detectors are essential.

- Compact neutron imager with single volume scatter camera: fast neutron direction and energy constrained by double scatter geometry





CONCLUSION

- Great strides in near detection: ruled out large fraction of RAA, conflicting sterile neutrino statements, toward high precision spectra measurement and fuel evolution, demonstrated surface operation
- Neutrino fluxes: conversion predictions reduced RAA, input from experiments helps, detective work with summation, awaiting normalized ILL spectra, tension in global sterile fits – will not go away any time soon.
- Far detector monitoring – excellent shape with WATCHMAN, Gd-SK and JUNO starting in the next 4-5 years.
- Application studies – more suitable for special case reactor in near field, or focus on farther afield. Not much impact on bomb detection.
- CENNS: great progress, CENNS detection at commercial reactors very close.
- Vigorous R&D in full 3D segmentation for full-event topology, novel scintillators, planning for large scale detectors, and directionality, background prediction on the surface, imaging for large detectors and neutrons

THANK YOU TO THE ORGANIZERS FOR A SUPERB WORKSHOP AND PARTICIPANTS FOR VALUABLE TALKS AND DISCUSSIONS